

PALOMA: A MAGNETIC CV BETWEEN POLARS AND INTERMEDIATE POLARS

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ABSTRACT

We present analyses of archival X-ray data obtained from the *XMM-Newton* satellite and optical photometric data obtained from 1 m class telescopes of ARIES, Nainital of a magnetic cataclysmic variable (MCV) Paloma. Two persistent periods at 156 ± 1 minutes and 130 ± 1 minutes are present in the X-ray data, which we interpret as the orbital and spin periods, respectively. These periods are similar to those obtained from the previous as well as new optical photometric observations. The soft-X-ray excess seen in the X-ray spectrum of Paloma and the averaged X-ray spectra are well fitted by two-temperature plasma models with temperatures of $0.10^{+0.02}_{-0.01}$ and $13.0^{+0.5}_{-0.5}$ keV with an Fe K α line and an absorbing column density of 4.6×10^{22} cm⁻². This material partially covers 60 ± 2 % of the X-ray source. We also present the orbital and spin-phase-resolved spectroscopy of Paloma in the 0.3 – 10.0 keV energy band and find that the X-ray spectral parameters show orbital and spin-phase dependencies. New results obtained from optical and X-ray studies of Paloma indicate that it belongs to a class of a few magnetic CVs that seem to have the characteristics of both the polars and the intermediate polars.

Subject headings: accretion, accretion disks — binaries: close — magnetic CV, cataclysmic variables — stars: individual (Paloma) — X-rays: stars

1. INTRODUCTION

Magnetic cataclysmic variables (MCVs) are evolved, semi-detached interacting binaries containing a magnetic white dwarf (WD), which accretes material from a Roche lobe filling red dwarf star (Warner 1995). These stars are characterized by strong X-ray emission, high-excitation optical spectra, very stable X-ray and optical periods in their light curves and optical polarization. MCVs are broadly classified into two categories: polars and intermediate polars (IPs). Polars usually show synchronous or near-synchronous rotation of the magnetized WD with the orbital motion of the binary system and have a magnetic field of ≥ 10 MG. The high magnetic field strength in the polars causes the accretion stream flows along the magnetic field lines to its poles and suppresses the formation of the accretion disk leading to a synchronous motion. However, there are some MCVs (e.g., V1432 Aql, BY Cam, CD Ind, and V1500 Cyg) for which the spin period (P_ω) and the orbital period (P_Ω) differ by about 2 % or less. These systems are thought to be polars and asynchronism is thought to arise due to a recent nova explosion (Norton et al. 2004). The IPs possess a magnetic field of less than 10 MG and the WD rotation is not synchronized with the orbital motion (see Hellier 2002). The weaker magnetic field in the IPs allows the material from the companion red dwarf star to form an accretion disk, though the inner part of the disk is disrupted into accretion curtains and columns before dumping the material to the magnetic poles of the WD (Rosen et al. 1988). There are two other systems namely RX J0524+42 (Paloma) and V697 Sco, which are described as nearly synchronous IPs, with $P_\omega = (0.7 - 0.9) P_\Omega$. Paloma also lies in the period gap and is thought to be currently in the process of attaining synchronism and

evolving into a polar (Norton et al. 2004; Schwarz et al. 2007). The orbital period distribution of MCVs shows that the P_Ω of polars are in the range of 1.0 – 10.0 hr, while a majority of the IPs have orbital periods longer than the period gap of 2 – 3 hrs (Scaringi et al. 2010). The period gap is no longer seen to exist for polars (Norton et al. 2004; Scaringi et al. 2010).

The X-ray luminosities of IPs are greater than those of polars by a factor of ~ 10 , attributed mainly to the higher accretion rates (e.g., Channugam et al. 1991). The simplest scenario for X-ray production in MCVs is that the magnetically channeled accretion column impacts the poles of WD, with supersonic velocities leading to the formation of strong shocks. In the post-shock region, the matter cools via thermal bremsstrahlung and cyclotron radiation (Aizu 1973; Wu et al. 1994; Cropper et al. 1999) depending upon the magnetic field strength of WD. Therefore, a majority of the IPs are hard-X-ray emitters because the hot plasma of the post-shock region cools on the surface of the WD via thermal bremsstrahlung and the temperature of the post-shock region is $\sim 50 - 600$ MK (Warner 1995; Hellier 2001). Some IPs (PQ Gem, V405 Aur, UU Col, and MU Cam) have been recognized to possess a soft-X-ray emission component (see Haberl & Motch 1995; Burwitz et al. 1996; Staude et al. 2003). In polars, cyclotron cooling is more efficient (Lamb & Masters 1979); therefore, a part of the downward emitted hard X-rays and cyclotron radiation is absorbed by the WD surface and re-emitted in the soft X-rays.

In this work, we present a detailed analysis of X-ray and optical photometric observations of Paloma. This object was first characterized by Schwarz et al. (2007) using optical photometry and *ROSAT* X-ray observa-

tions. They reported an orbital period of 157 minutes and two spin periods of 146 and 136 minutes. With an orbital period in the period gap, Schwarz et al. (2007) suggested that Paloma might be the first bona fide transition object between the DQ Her (IPs) and AM Her (Polars) system with a WD currently in the process of synchronization. The paper is organized as follows. In the next section, we present the observations and data reduction. Section 3 contains an analysis and the results of the X-ray and optical observations, including X-ray and optical timing analyses as well as an X-ray spectral analysis and the result of the phase-resolved X-ray spectroscopy. Finally, we present a discussion and summary in section 4 and 5, respectively.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-Ray Observations

Paloma was observed with the *XMM-Newton* satellite (Jansen et al. 2001) using European Photon Imaging Camera (EPIC; Strüder et al. 2001; Turner et al. 2001) and Reflecting Grating Spectrometer (RGS; den Herder et al. 2001) instruments on 2006 February 22 at 23:23:47 UT for 60 ks in revolution 1137. The EPIC instrument consists of three cameras containing MOS1 and MOS2 (Turner et al. 2001) and PN (Strüder et al. 2001) CCDs, providing extremely sensitive imaging observations over a field of view (fov) of 30 arcmins and an energy range of 0.2 – 10.0 keV. We used standard *XMM-Newton* Science Analysis System (SAS) software package (version–14.0.0) for data reduction with updated calibration files. The preliminary processing of raw EPIC Observation Data Files was done using the EPCHAIN and EMCHAIN tasks, which allow calibration both in energy and astrometry of the events registered in each CCD chip and combine them in a single data file for MOS and PN detectors. The background contribution is particularly relevant at high energies, therefore, for further analysis, we have selected the energy range between 0.3 and 10.0 keV. Calibrated and concatenated event list files were extracted using SAS tasks EVSELECT. Data were corrected to the barycenter of the solar system with the BARYCEN task. We have also checked the data for high background proton flares and data that were free from this effect. Subsequently, the EPATPLOT task was used for checking the existence of pile up but it was not observed in the CCD during the observations. The X-ray light curves and spectra of Paloma were extracted from a circular region with a radius 20 arcsecs around the source. The background was chosen from several source-free regions each with a radius of 20 arcsecs on the detectors surrounding the source. Furthermore, the SAS task EREGIONANALYSE was also used for the final region selection. Data with single and double-pixel events, i.e., PATTERN = 0–4 for PN and PATTERN = 0–12 for MOS with FLAG = 0 were used for further analysis. We used the tool EPICLCCORR to correct for good time intervals, dead time, exposure, point-spread function, quantum efficiency, and background subtraction. The sky region surrounding the target in MOS CCDs was contaminated by events from another region of the sky accumulated during the slew. To solve this problem, we removed the initial one hour of observations because the attitude information allowed us to see when the instrument was on

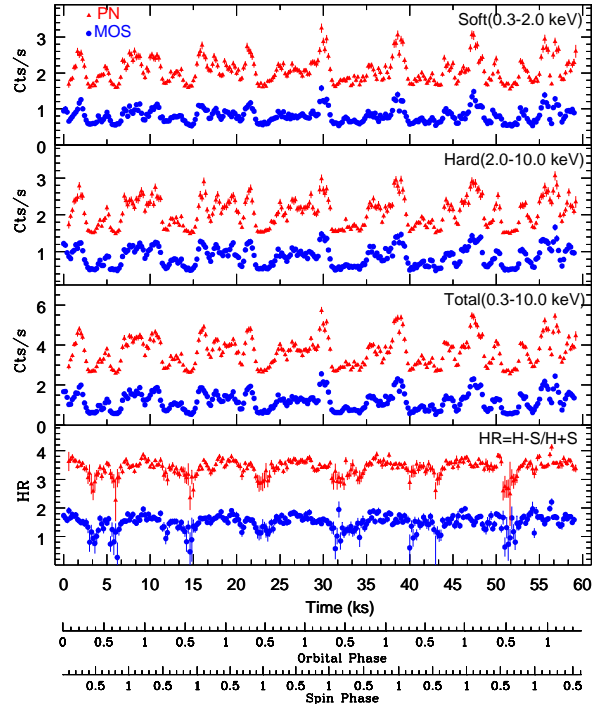


Figure 1. X-ray light curves of Paloma at three energy bands named soft, hard, and total. The bottom panel is an HR curve, where HR is defined as $(H-S)/(H+S)$; H and S are count rates in hard and soft energy bands, respectively. In each panel, the upper curve is for PN data while the lower curve is for MOS data. Orbital and spin phases are also shown.

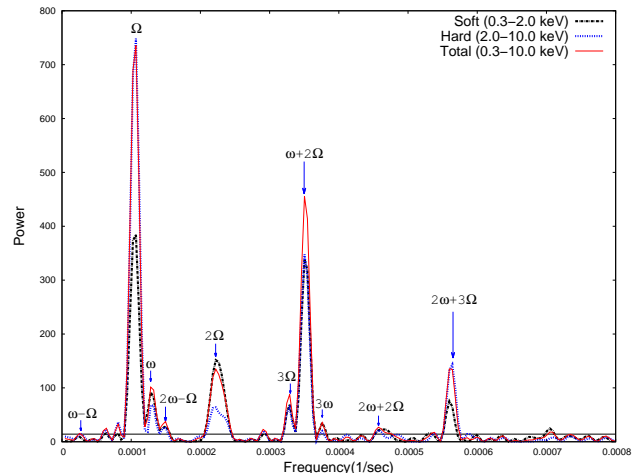
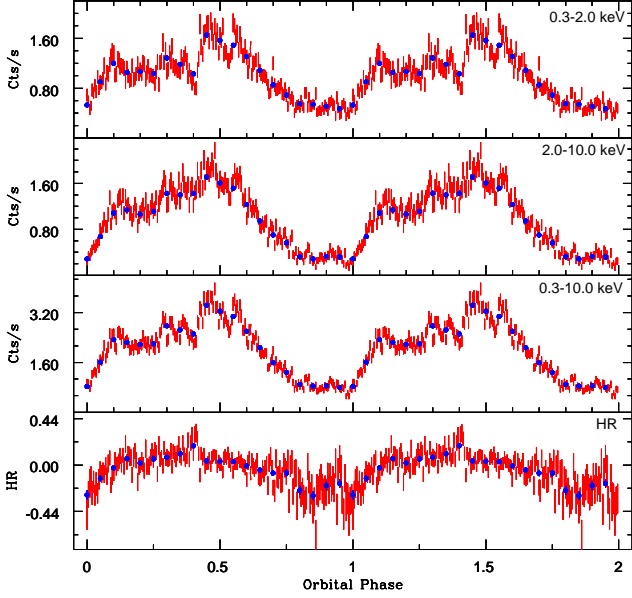
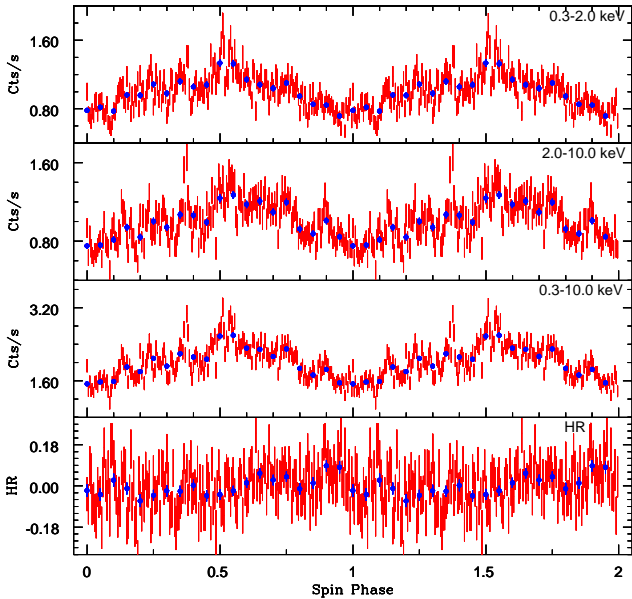


Figure 2. Power spectra of Paloma obtained from the EPIC-PN data in the soft, hard, and total energy bands.

target and it showed that the pointing was stable after removing one hour of observation. We, therefore, created a good time interval file to remove all the events pertaining to the period before the stable pointing. The SAS task ESPECGET was used to generate the background corrected spectra, which also computes the photon redistribution matrix and the ancillary matrix. The spectra were rebinned for a minimum of 20 counts per bin using grppha. RGSPROC was run in order to extract the RGS event files and spectra. Further temporal and spectral analyses were done by HEASOFT version 6.17.



(a)



(b)

Figure 3. Folded X-ray light curves of Paloma in soft, hard, and total energy bands, where solid dots are folded light curve with phase bin of 0.05. The folded HR curve is also shown in the bottom panels.

2.2. Optical Observations

R-band photometric observations of Paloma were obtained in 2014 October and November using the 1.04 m Sampurnanand Telescope (ST; Sinvhal et al. 1972) at Nainital and 1.3 m Devasthal Fast Optical Telescope (DFOT) located at Devasthal, India (Sagar et al. 2011). The ST has Ritchey–Chretien (RC) optics with a $f/13$ beam at the Cassegrain focus. The ST is equipped with a $2k \times 2k$ CCD (read noise = $13.7 e^-$ and gain = $10 e^-/\text{ADU}$). Each pixel of the CCD chip has a dimension of $24 \mu\text{m}^2$ and it covers an fov of $13' \times 13'$. Observations were carried out in a

Table 1

Periods corresponding to dominant peaks in the power spectra of Paloma obtained from X-ray and optical data.

Identification	X-ray		Optical
	PN (0.3–10.0 keV)	MOS (0.3–10.0 keV)	Photometry
	Period (minutes)	Period (minutes)	Period (minutes)
P_Ω	156 ± 1	158 ± 1	157.1 ± 0.2
P_ω	130 ± 1	127 ± 2	136.36 ± 0.01
$P_{\omega'}$	–	–	147.5 ± 0.1
$P_{(2\omega - \Omega)}$	111 ± 2	113 ± 3	–
$P_{2\Omega}$	75 ± 1	73 ± 1	78.6 ± 0.1
$P_{3\Omega}$	50.6 ± 0.2	50.5 ± 0.4	–
$P_{(\omega + 2\Omega)}$	47.5 ± 0.1	47.5 ± 0.1	–
$P_{3\omega}$	44.3 ± 0.2	44.3 ± 0.4	–
$P_{(2\omega + 2\Omega)}$	36.4 ± 0.2	36.5 ± 0.3	–
$P_{(2\omega + 3\Omega)}$	29.7 ± 0.1	29.6 ± 0.1	–
$P_{(\omega + \Omega)}$	–	–	73.00 ± 0.04
$P_{\omega - \Omega, obs}$	780 ± 85	668 ± 121	1002.5 ± 1.0

2×2 pixel² binning mode in order to increase the signal-to-noise ratio. The 1.3 m is also RC design with a $f/4$ beam at the Cassegrain focus. The telescope is equipped with a $2k \times 2k$ Andor CCD (read noise = $7e^-$ and gain = $2 e^-/\text{ADU}$ at 1000 kHz readout speed) with a pixel size of $13.5 \mu\text{m}^2$. The fov of CCD is $\sim 18' \times 18'$. The exposure time per frame was five minutes in both the telescopes. Several bias and twilight sky flat frames were also taken during the observing runs. The pre-processing (i.e., bias subtraction and flat fielding) and aperture photometry were performed using IRAF¹ software. The R-band differential photometry (i.e., variable minus comparison star) was done by using the same comparison star as used by Schwarz et al. (2007).

3. ANALYSIS AND RESULTS

3.1. X-Ray Data

3.1.1. Light Curves and Power Spectra

The background-subtracted X-ray light curves obtained from three EPIC instruments in the soft (0.3–2.0 keV), hard (2.0–10.0 keV), and total (0.3–10.0 keV) energy bands along with the hardness ratio curve are shown in Figure 1. The hardness ratio (HR) is defined as $(H-S)/(H+S)$; where H and S are count rates in hard and soft energy bands, respectively. The binning time of all light curves is 200 s. The light curves are continuous and show periodic intensity variations. We performed a Fourier Transform (FT) of the *XMM-Newton* data using Lomb–Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986) as implemented in the STARLINK PERIOD PROGRAM. Figure 2 show the Lomb–Scargle power spectra of EPIC-PN timing data in the total, soft, and hard energy bands. We have also calculated the False Alarm Probability (see Horne & Baliunas 1986) in order to check the significance of detected peaks. The horizontal line in Figure 2 shows a 99% significance level. The power spectra of MOS and PN data show consistent periods corresponding to the peak frequencies and are given in Table 1. The frequencies in the power spectra as obtained from the PN data correspond to the longest periods of 156 ± 1 minutes and 130 ± 1 minutes which appear to be the orbital and spin periods, respectively. The error on these periods were derived by using the method given in Horne & Baliunas

¹ IRAF is distributed by the national optical astronomy observatories, USA.

Table 2
Values of X-ray spectral parameters Obtained from the Best-fit models to the data.

Models(→) Parameters(↓)	A	B	C	D	E	F
tbabs (N_{H1})	4.4 ^{+0.4} _{-0.4}	7.5 ^{+1.8} _{-1.6}	7.9 ^{+0.9} _{-0.9}	2.8 ^{+0.5} _{-0.5}	3.8 ^{+0.4} _{-0.4}	6.6 ^{+1.0} _{-1.0}
pcfabs (N_{H2})	5.5 ^{+0.3} _{-0.3}	6.0 ^{+0.4} _{-0.4}	6.2 ^{+0.4} _{-0.4}	3.0 ^{+0.4} _{-0.4}	4.0 ^{+0.4} _{-0.4}	4.6 ^{+0.6} _{-0.5}
pcf	0.66 ^{+0.01} _{-0.01}	0.65 ^{+0.01} _{-0.01}	0.64 ^{+0.01} _{-0.01}	0.55 ^{+0.03} _{-0.03}	0.59 ^{+0.02} _{-0.02}	0.60 ^{+0.02} _{-0.02}
reflect (R_{refl})	...	...	...	...	2.8 ^{+0.7} _{-0.7}	2.4 ^{+0.8} _{-0.7}
bb (kT)	...	0.09 ^{+0.01} _{-0.01}	...	2.6 ^{+0.3} _{-0.2}	...	...
n ($\times 10^{-5}$)	...	0.7 ^{+0.3} _{-0.3}	...	5.0 ^{+0.6} _{-0.6}	...	...
apec (kT_1)	...	...	0.11 ^{+0.01} _{-0.01}	1.4 ^{+0.2} _{-0.1}	...	0.10 ^{+0.02} _{-0.01}
n_1 ($\times 10^{-3}$)	...	...	1.0 ^{+0.01} _{-0.01}	0.07 ^{+0.03} _{-0.02}	...	0.3 ^{+0.3} _{-0.2}
apec (kT_2)	12.6 ^{+0.6} _{-0.6}	12.6 ^{+0.5} _{-0.6}	12.6 ^{+0.6} _{-0.6}	10.1 ^{+0.8} _{-0.8}	13.1 ^{+1.4} _{-0.5}	13.0 ^{+0.5} _{-0.5}
n_2 ($\times 10^{-3}$)	4.4 ^{+0.1} _{-0.1}	4.4 ^{+0.1} _{-0.1}	4.4 ^{+0.1} _{-0.1}	2.5 ^{+0.3} _{-0.3}	3.5 ^{+0.2} _{-0.2}	3.7 ^{+0.2} _{-0.2}
EW	116 ⁺¹⁸ ₋₁₉	113 ⁺¹⁸ ₋₁₉	112 ⁺¹⁷ ₋₁₈	92 ⁺¹⁷ ₋₁₈	95 ⁺¹⁸ ₋₁₇	97 ⁺¹⁷ ₋₁₇
n_g ($\times 10^{-5}$)	1.0 ^{+0.2} _{-0.2}	1.0 ^{+0.1} _{-0.1}	0.9 ^{+0.1} _{-0.1}	0.8 ^{+0.1} _{-0.1}	0.6 ^{+0.1} _{-0.1}	0.7 ^{+0.1} _{-0.1}
X-ray flux (f_X)	0.610 ^{+0.006} _{-0.006}	0.630 ^{+0.011} _{-0.010}	0.610 ^{+0.006} _{-0.006}	0.630 ^{+0.007} _{-0.007}	0.625 ^{+0.007} _{-0.007}	0.640 ^{+0.008} _{-0.008}
X-ray luminosity (L_X)	4.18 ^{+0.04} _{-0.04}	4.32 ^{+0.08} _{-0.07}	4.18 ^{+0.04} _{-0.04}	4.32 ^{+0.05} _{-0.05}	4.30 ^{+0.05} _{-0.05}	4.40 ^{+0.05} _{-0.05}
χ^2_ν (dof)	1.16(1782)	1.15(1780)	1.13(1780)	1.09(1778)	1.13(1781)	1.12(1779)

Note. — Where models A—tbabs×pcfabs(apec+Gauss), B—tbabs×pcfabs(bb+apec+Gauss), C—tbabs×pcfabs(apec+apec+Gauss), D—tbabs×pcfabs(bb+apec+apec+Gauss), E—tbabs×reflect×pcfabs(apec+Gauss), and F—tbabs×reflect×pcfabs(apec+apec+Gauss). N_{H1} = Absorption due to galactic hydrogen column in units of 10^{20} cm⁻², N_{H2} is the partial covering absorber density, i.e., absorption due to partial covering of the X-ray source by the neutral hydrogen column in units of 10^{22} cm⁻², pcf is the covering fraction of the partial absorber, bb is the blackbody temperature in keV, n is the normalization constant of the blackbody, kT_1 and kT_2 are apec temperatures in units of keV, n_1 and n_2 are the normalization constants of apec, EW is equivalent width of the Fe K α line in units of eV, n_g is normalization constant of Gaussian, f_X is the X-ray flux derived for 0.3-10.0 keV energy band in units of 10^{-11} erg cm⁻² s⁻¹, and L_X is the X-ray luminosity calculated in units of 10^{31} erg s⁻¹ by assuming a distance of 240 pc. All the errors are with a 90% confidence interval for a single parameter ($\Delta\chi^2=2.706$).

(1986). Following the above interpretation, the beat period ($P_{beat} = P_\Omega P_\omega / P_\Omega - P_\omega$) was derived to be 780 minutes from the present X-ray data. The beat period also coincides with a sub-harmonic of orbital period $5 \times P_\Omega$ and spin period $6 \times P_\omega$. The frequency corresponding to the beat period was also present in the power spectra and marked by $\omega - \Omega$. The other dominant peaks in the power spectra correspond to periods of $P_{(2\omega - \Omega)} = 111 \pm 2$ minutes, $P_{2\Omega} = 75 \pm 1$ minutes, $P_{3\Omega} = 50.6 \pm 0.2$ minutes, $P_{(\omega + 2\Omega)} = 47.5 \pm 0.1$ minutes, $P_{3\omega} = 44.3 \pm 0.2$ minutes, $P_{(2\omega + 2\Omega)} = 36.4 \pm 0.2$ minutes, and $P_{(2\omega + 3\Omega)} = 29.7 \pm 0.1$ minutes. The power spectra in all energy bands show similar peak frequencies. The peak powers corresponding to the periods $P_{(\omega - \Omega)}$, P_Ω , $P_{(\omega + 2\Omega)}$, and $P_{(2\omega + 3\Omega)}$ were found to be more in the hard band than those in the soft band. However, powers of all other peaks were found to be more in the soft band compared to that in the hard band. We have folded the PN data using the ephemeris $HJD_0 = 2450897.35376$ as given by Schwarz et al. (2007). The folded X-ray light curves and HR curves corresponding to the derived orbital and spin periods are shown in Figure 3. The periodic modulation in all energy bands is clearly seen. Orbital and spin period modulations were also seen in HR curve, which is an indication of the dependence of spectral parameters on the orbital and spin phases.

3.1.2. X-ray Spectral Analysis

The background-subtracted X-ray spectra of Paloma are shown in Figure 4, where strong broadband continuum along with the strong emission line features at 6.4 keV are clearly seen. The inset in Figure 4 shows an enlarged view of the 6.0–7.5 keV energy range, which contains the Fe K α fluorescent line at 6.4 keV and 6.7, 6.95 keV lines from ionized Fe XXV and Fe XXVI, respectively. Spectral fits were performed on the PN and MOS data using XSPEC version-12.9.0 (Arnaud 1996; Dorman & Arnaud 2001) with various models/combinations of models. These models were blackbody (bb), bremsstrahlung (bremss), astrophysical plasma emission code (apec; Smith et al. 2001), and Gaussian. A common absorption component (tbabs) was used in all models/combinations of models. A single bremsstrahlung or

blackbody temperature model with tbabs component produced an unacceptable fit with reduced $\chi^2_\nu \geq 3.0$. The apec single temperature plasma emission model with the tbabs component also yielded an unacceptably high value of χ^2_ν of 3.09. Though the apec plasma emission model can account for the continuum and several emission lines, it is not able to account for the strong Fe line at 6.4 keV. Therefore, an additional Gaussian line at 6.4 keV was added to the single component of apec resulting in an improved χ^2_ν of 1.5 (dof 1790). All the above combinations of models gave unacceptably high values of χ^2 . Therefore, we fitted all the above models/combinations of models with partially covering absorption model (pcfabs), which gave a better fit but still with an unacceptable χ^2_ν . However, the model tbabs×pcfabs(apec+Gauss) [model A] gave an acceptable value of reduced χ^2_ν of 1.16 (dof 1782), but this model was unable to explain the excess around 0.5 keV, which is clearly seen in the ratio plot of Figure 4 (a) indicating the presence of low-temperature component. We therefore, added a blackbody component along with the single apec temperature as tbabs×pcfabs(bb+apec+Gauss) [model B], but there was no improvement in the χ^2_ν and the excess near 0.5 keV was still present on the spectra (see Figure 4 (b)). The use of two apec components along with a Gaussian, modeled as tbabs×pcfabs(apec+apec+Gauss) [model C] with solar photospheric abundances from Anders & Grevesse (1989), slightly improved the ($\chi^2_\nu = 1.13$, dof = 1780), and provides a better fit to the spectra near 0.5 keV (see Figure 4 (c)). In order to obtain the best fit, we have also fitted the spectra by adding a blackbody model as tbabs×pcfabs(bb+apec+apec+Gauss) [model D], which improves the χ^2_ν to 1.09, (dof = 1778) but the excess near 0.5 keV is still present (see Figure 4 (d)). In all four models, we obtained the equivalent width (EW) of the Fe K α emission line more than ~ 100 eV (see Table 2). To account for the derived large EW, the column density of cold matter should be as high as 10^{23} cm⁻² (see Inoue 1985), while this value is found a factor of ~ 10 lower for the partial absorber in models A, B, C, and D. This suggests the presence of the contribution of a Compton reflected continuum from the WD, which is ex-

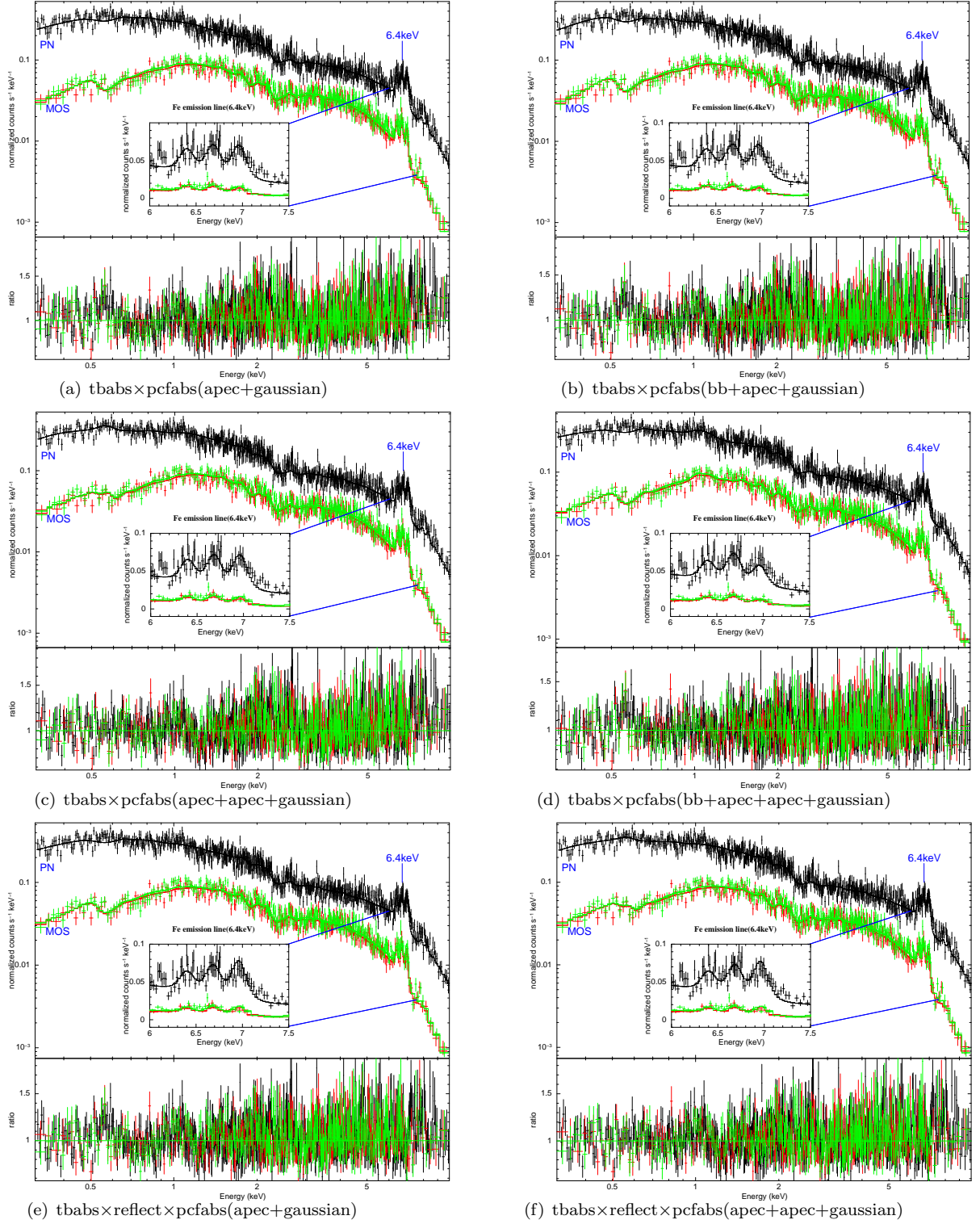


Figure 4. EPIC-PN (top) and MOS (bottom) spectra of Paloma fitted simultaneously with the six composite models. The zoomed spectra and the model fit around the Fe-K α region are shown in the inset. The bottom panel shows the χ^2 contribution of data points for the best-fitting model in terms of ratio.

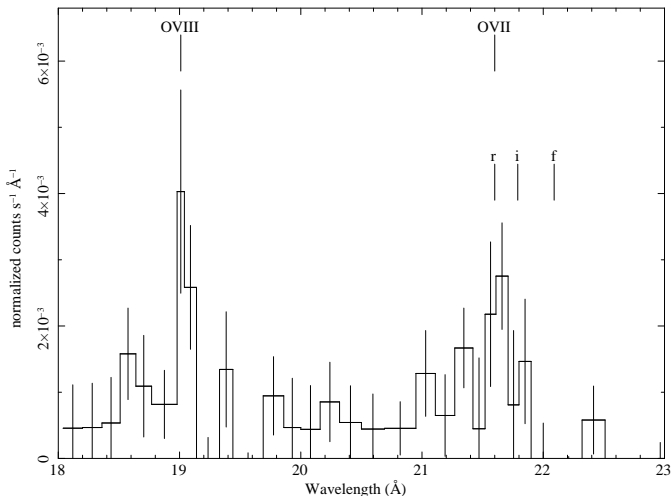


Figure 5. RGS spectra near the O VIII and O VII line.

pected to go along with the fluorescent iron line (Matt et al. 1991; Done et al. 1992; Ezuka & Ishida 1999). Therefore, to take into account a reflected continuum of the plasma emission due to the Fe K α at 6.4 keV, we have also used the reflection model, which is a convolution type of model describing the reflectivity of a neutral material (Magdziarz & Zdziarski 1995). Including this new model component with a combination of other models as `tbabs×reflect×pcfabs(apec+Gauss)` [model E], the model parameters remain the same as in model A and the excess was also seen near 0.5 keV (see Figure 4 (e)). Finally, we adopt model F for the spectral fitting, which is `tbabs×reflect×pcfabs(apec+apec+Gaussian)`. This model improves the value of χ^2_ν to 1.12 (dof=1779) and also fit the spectra near 0.5 keV (see Figure 4 (f)). In the above combinations of models keeping the line width parameter free in the Gaussian model does not fit the Gaussian line well and parameter value pegged at the upper limit. Therefore, to fix the value of the line width in the Gaussian, we changed the line width with the values 0.005, 0.01, 0.02, 0.05, 0.1, 0.15, and 0.2 keV and found that the values of line widths > 0.02 keV begin to merge the line with the continuum, while when line widths < 0.02 keV are narrower than observed and in both cases there is no change in the value of χ^2 and spectral parameters. The best fit was thus obtained when we have fixed the width of the Gaussian line at 0.02 keV. The spectral parameters derived from the simultaneous fitting to both EPIC-PN and MOS spectra using model A, B, C, D, E, and F are given in Table 2. The error bars quoted here are with 90% confidence limit for a single variable parameter. The best-fit value of the partial absorber hydrogen column density (N_{H2}) was $4.6^{+0.6}_{-0.5} \times 10^{22} \text{ cm}^{-2}$ with a covering fraction (pcf) of 60 ± 2 percent and apec temperatures (kT_1 and kT_2) of $0.10^{+0.02}_{-0.01}$ and $13.0^{+0.5}_{-0.5}$ keV. The galactic hydrogen column density (N_{H1}) corrected flux (f_X) was calculated by using the ‘cflux’ model. The X-ray luminosity of Paloma was calculated by assuming a distance of 240 pc (Schwarz et al. 2007) in the energy band 0.3 – 10.0 keV and is given in Table 2.

Spectral data from RGS were of poorer quality compared to PN and MOS data and are shown in Figure 5. The O VIII Ly α at 19.1 Å and the O VII He-like triplet at 21.9 Å are seen in the RGS spectra. The detected O VII line was likely to be a blend of the resonant (r), intercombination (i), and forbidden (f) lines, but with this noisy data spectra fits with any value of model (Gaussian) parameter. Therefore, finally, we have not attempted the spectral model fitting on RGS data.

3.1.3. Orbital and Spin-phase-resolved X-ray Spectroscopy

In order to trace the dependence of X-ray spectral parameters on orbital and spin phases, we performed orbital and spin-phase-resolved spectroscopy. The orbital and spin-phase spectra from EPIC-PN and MOS data were extracted for all five equal phase intervals of 0.2 from phase 0 to 1. Extracted spectra from both the detectors were simultaneously fitted for each interval with the best-fit model F. Initially, we allowed the apec temperatures to vary during the fit in all the five (orbital and spin) phase intervals, but that adjusted the value of other parameters such that the spectral fitting gave unacceptably high value of χ^2 . Therefore, the N_{H1} and temperatures of apec component (kT_1 and kT_2) were fixed at the values obtained from average spectral fitting. The free parameters were N_{H2} , pcf, relative normalization of the reflection component (R_{refl}), normalizations of apec (n_1 and n_2), and Gauss (n_g) models. We also derived the EW from the spectral fit in each orbital and spin-phase segment. Individual parameters obtained from the orbital and spin-phase-resolved spectral analysis are given in Table 3. The variations in N_{H2} , pcf, R_{refl} , EW, n_g , and unabsorbed flux f_X are shown in Figure 6. We find an anti-correlation between f_X and N_{H2} in both (orbital and spin) phase spectral analyses, while pcf and f_X are correlated with the orbital phase and anti-correlated with the spin phase. The variations of the R_{refl} and EW of the fluorescent line increases at the spin minimum phase. The normalization of the Fe K α emission line is also dependent on the spin and the orbital phases, i.e., the variations in line flux are correlated with changes in f_X .

3.2. Optical Photometry

Figure 7 shows the R-band light curve of Paloma for different nights. It shows multiscale time variability and strong flickering with optical pulsations in the light curve. The light curve appeared to show either a single hump or double-humped periodic variation. The Lomb–Scargle power spectra of optical R-band data is shown in the top panel of Figure 8, which is noisier compared to the power spectrum from X-ray data. Therefore, the CLEAN algorithm (Roberts et al. 1987) was applied to the data, which basically deconvolves the spectral window from the discrete Fourier power spectrum (or dirty spectrum) and produces a CLEAN spectrum. The CLEANed power spectra presented here were obtained after 100 iterations of the CLEAN procedure with a loop gain of 0.1. We found six significant peaks corresponding to periods given in Table 1. These periods correspond to the frequency components at $\omega - \Omega$, Ω , ω' , ω , 2Ω , and $\omega + \Omega$; where ω and ω' are two spin periods. The error in the period calculation was set by the finite resolution of the power spectrum and was determined as $P^2/2t_{max}$, where P is the period and t_{max} is the duration of the observations (see Roberts et al. 1987). The photometric data were folded using the periods P_Ω and P_ω and are shown in Figures 9 (a) and (b), respectively. On October 29, and November 18 and 20, clear double-humped structure was seen in orbital as well as spin-phase-folded light curves, but it disappeared on the next night, October 30. On the other hand, November 5, 14, 15, and 19 orbital phase-folded light curves seem to show a double-humped structure, while in the spin-phase-folded light curve the second peak is less prominent. On October 30 and November 4 modulations with orbital phases appear to be maximum around phases ($\sim 0.5 - 0.6$) and ($\sim 0.4 - 0.5$), respectively, while these variations are interrupted by a broad, eclipse-like feature centered around the spin phases ($\sim 0.3 - 0.4$) and ($\sim 0.4 - 0.5$) on both nights, respectively, with an amplitude of 0.8 mag.

4. DISCUSSION

We have carried out analyses of X-ray and optical photometric data of an MCV Paloma. Using the X-ray data from *XMM-Newton*, we derive 10 significant periods in Paloma,

Table 3

The best fit X-ray spectral parameters derived from the analysis of PN and MOS data at different orbital and spin phases.

Model	Parameters	Orbital Phase				
		0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
pcfabs	$N_{\text{H}2}(\times 10^{22} \text{ cm}^{-2})$	$6.2^{+1.2}_{-1.2}$	$10.0^{+6.5}_{-4.3}$	$4.8^{+0.9}_{-0.8}$	$3.8^{+0.7}_{-0.6}$	$3.0^{+0.6}_{-0.5}$
	pcf	$0.53^{+0.02}_{-0.05}$	$0.38^{+0.04}_{-0.13}$	$0.61^{+0.04}_{-0.04}$	$0.63^{+0.03}_{-0.03}$	$0.56^{+0.03}_{-0.03}$
reflect	R_{refl}	$0.00005^{+0.00002}_{-0.00002}$	$0.0034^{+0.0008}_{-0.0008}$	$1.74^{+1.52}_{-1.35}$	$5.80^{+1.70}_{-1.60}$	$3.7^{+1.3}_{-1.2}$
apec	$n_1(\times 10^{-3})$	$0.15^{+0.07}_{-0.07}$	$0.70^{+0.04}_{-0.04}$	$0.36^{+0.11}_{-0.11}$	$0.42^{+0.13}_{-0.12}$	$0.58^{+0.12}_{-0.12}$
apec	$n_2(\times 10^{-3})$	$2.31^{+0.05}_{-0.02}$	$1.27^{+0.03}_{-0.22}$	$3.98^{+0.40}_{-0.40}$	$4.49^{+0.45}_{-0.40}$	$4.89^{+0.36}_{-0.36}$
Gaussian (6.4 keV)	$n_g(\times 10^{-5})$	$0.4^{+0.2}_{-0.2}$	$0.2^{+0.1}_{-0.1}$	$0.7^{+0.3}_{-0.3}$	$0.8^{+0.3}_{-0.3}$	$0.9^{+0.3}_{-0.3}$
EW	Fe K α (eV)	85^{+69}_{-57}	40^{+21}_{-27}	99^{+41}_{-44}	91^{+32}_{-33}	94^{+31}_{-34}
X-ray flux (0.3–10.0 keV)	$f_X(\times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1})$	$0.36^{+0.01}_{-0.01}$	$0.21^{+0.01}_{-0.01}$	$0.66^{+0.02}_{-0.02}$	$0.91^{+0.02}_{-0.02}$	$0.96^{+0.02}_{-0.02}$
X-ray luminosity (0.3–10.0 keV)	$L_X(\times 10^{31} \text{ erg s}^{-1})$	$2.47^{+0.07}_{-0.07}$	$1.44^{+0.07}_{-0.07}$	$4.53^{+0.13}_{-0.13}$	$6.24^{+0.13}_{-0.13}$	$6.59^{+0.13}_{-0.13}$
	χ^2_ν (dof)	1.13(358)	1.28(245)	1.05(555)	1.10(675)	0.91(752)
Model	Parameters	Spin Phase				
		0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
pcfabs	$N_{\text{H}2}(\times 10^{22} \text{ cm}^{-2})$	$4.6^{+1.3}_{-1.0}$	$3.4^{+0.7}_{-0.6}$	$4.3^{+1.0}_{-1.0}$	$4.8^{+1.2}_{-1.0}$	$6.8^{+1.7}_{-1.5}$
	pcf	$0.54^{+0.05}_{-0.06}$	$0.58^{+0.03}_{-0.04}$	$0.56^{+0.05}_{-0.05}$	$0.60^{+0.05}_{-0.05}$	$0.64^{+0.03}_{-0.06}$
reflect	R_{refl}	$2.01^{+1.40}_{-1.24}$	$2.80^{+2.05}_{-1.80}$	$0.83^{+0.03}_{-0.01}$	$3.27^{+1.96}_{-1.73}$	$3.91^{+2.32}_{-2.00}$
apec	$n_1(\times 10^{-3})$	$0.28^{+0.09}_{-0.09}$	$0.53^{+0.13}_{-0.12}$	$0.15^{+0.10}_{-0.10}$	$0.37^{+0.12}_{-0.10}$	$0.24^{+0.11}_{-0.10}$
apec	$n_2(\times 10^{-3})$	$3.18^{+0.47}_{-0.40}$	$4.37^{+0.41}_{-0.36}$	$3.50^{+0.46}_{-0.40}$	$3.15^{+0.48}_{-0.40}$	$3.27^{+0.35}_{-0.50}$
Gaussian (6.4 keV)	$n_g(\times 10^{-5})$	$0.3^{+0.2}_{-0.2}$	$1.0^{+0.3}_{-0.3}$	$0.8^{+0.3}_{-0.2}$	$0.7^{+0.3}_{-0.3}$	$0.4^{+0.4}_{-0.3}$
EW	Fe K α (eV)	50^{+44}_{-44}	83^{+40}_{-41}	51^{+43}_{-42}	103^{+47}_{-48}	132^{+58}_{-48}
X-ray flux (0.3–10.0 keV)	$f_X(\times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1})$	$0.58^{+0.01}_{-0.01}$	$0.80^{+0.02}_{-0.02}$	$0.64^{+0.01}_{-0.01}$	$0.58^{+0.01}_{-0.01}$	$0.48^{+0.01}_{-0.01}$
X-ray luminosity (0.3–10.0 keV)	$L_X(\times 10^{31} \text{ erg s}^{-1})$	$3.98^{+0.07}_{-0.07}$	$5.49^{+0.13}_{-0.13}$	$4.39^{+0.07}_{-0.07}$	$3.98^{+0.07}_{-0.07}$	$3.29^{+0.07}_{-0.07}$
	χ^2_ν (dof)	0.90(458)	1.04(591)	0.93(491)	1.21(445)	1.05(384)

Note: Quoted error bars are with a 90% confidence limit for a single parameter.

including two fundamental periods of 156 ± 1 minutes and 130 ± 1 minutes. However, using our optical data, we derive seven significant periods in which P_Ω and P_ω are consistent with $\sim 1.5 \sigma$ level to that derived from X-ray data. The peaks corresponding to the frequencies Ω , ω , 2Ω , and $\omega + \Omega$ are well matched with those derived by Schwarz et al. (2007). The orbital modulation in the X-ray light curves is generally explained by the absorption of X-rays emitted near the WD surface by material fixed in the orbital frame, but a strong signal at the orbital period in the X-ray power spectra of Paloma indicates that an explicit orbital modulation is most likely due to the attenuation introduced by the impact site of the accretion stream with the accretion disk or magnetosphere. On the other hand, X-ray modulation at the spin period can arise due to the self-occultation of emission regions by the WD or due to photoelectric absorption and electron scattering in the accretion curtain (Norton et al. 1996). The occurrence of the spin peak indicates that the symmetry of the two pole caps is broken and the amount of asymmetry depends on whether the signal corresponding to the rotation of the asymmetrically placed pole is strong or weak, i.e., the degree of asymmetry is proportional to the power of the spin peak (Wynn & King 1992). Along with the spin frequency, the presence of significant peaks in the X-ray power spectrum at $\omega - \Omega$, Ω , $2\omega - \Omega$, 2Ω , 3Ω , $\omega + 2\Omega$, 3ω , $2\omega + 2\Omega$, and $2\omega + 3\Omega$ also predict that Paloma is an asymmetric system in which both the emission poles are not diametrically opposite and have slightly different emission properties (see Norton et al. 1996). Furthermore, the presence of significant power at spin, beat and $2\omega - \Omega$ frequencies suggest that Paloma is a disk-less accreting system (see Wynn & King 1992; Norton et al. 1996). Additionally, an increase in power of the beat or $2\omega - \Omega$

components accompanied by the decrease in power at the spin component as the X-ray energy increases is a characteristic of the disk-less accretion. This is clearly visible in the X-ray power density spectra of Paloma, which is further attributed to the absorption of low-energy photons by the accretion column itself. Other than the orbital, spin, and beat periods, photometric observations of Paloma show peaks at frequencies 2Ω and $\omega + \Omega$. Such similar positive and negative sideband frequencies corresponding to the spin and orbital periods are also observed from photometric observations in nearly synchronous IP V697 Sco (Warner & Woudt 2002), suggesting that Paloma may have a closer resemblance to V697 Sco.

MCVs occupy a wide range of parameter space in the $P_\omega - P_\Omega$ plane in which the evolution of these systems can be drawn from the degree of synchronization with the orbital period. Paloma is one of the few MCVs with an orbital period lying in the period gap ($\sim 2 - 3$ hr) and discovered as one of the nearly synchronous IPs (see Norton et al. 2004). The asynchronicity ($1 - P_\omega/P_\Omega$) of Paloma was found to be $\sim 16.6\%$ from the X-ray and optical data, which is slightly away from the line of synchronization. Furthermore, the values of $P_{(\omega, \omega')}/P_\Omega$ (~ 0.8) obtained from X-ray and optical analyses of Paloma satisfy the synchronization condition derived by Norton et al. (2004) i.e., $P_\omega/P_\Omega > 0.6$. The observed asynchronicity in Paloma suggests that it might be representative of a transition object currently in the process of attaining synchronism and evolving into polars.

In the X-ray power spectrum of Paloma, we have also found a specific signal at the beat frequency along with a long WD spin period ($P_\omega \sim 130$ minutes), and X-ray modulations show a single-peaked pulse profile as seen in some IPs FO Aqr, TX Col, BG CMi, AO Psc, V1223 Sgr, and RX J1712.6-

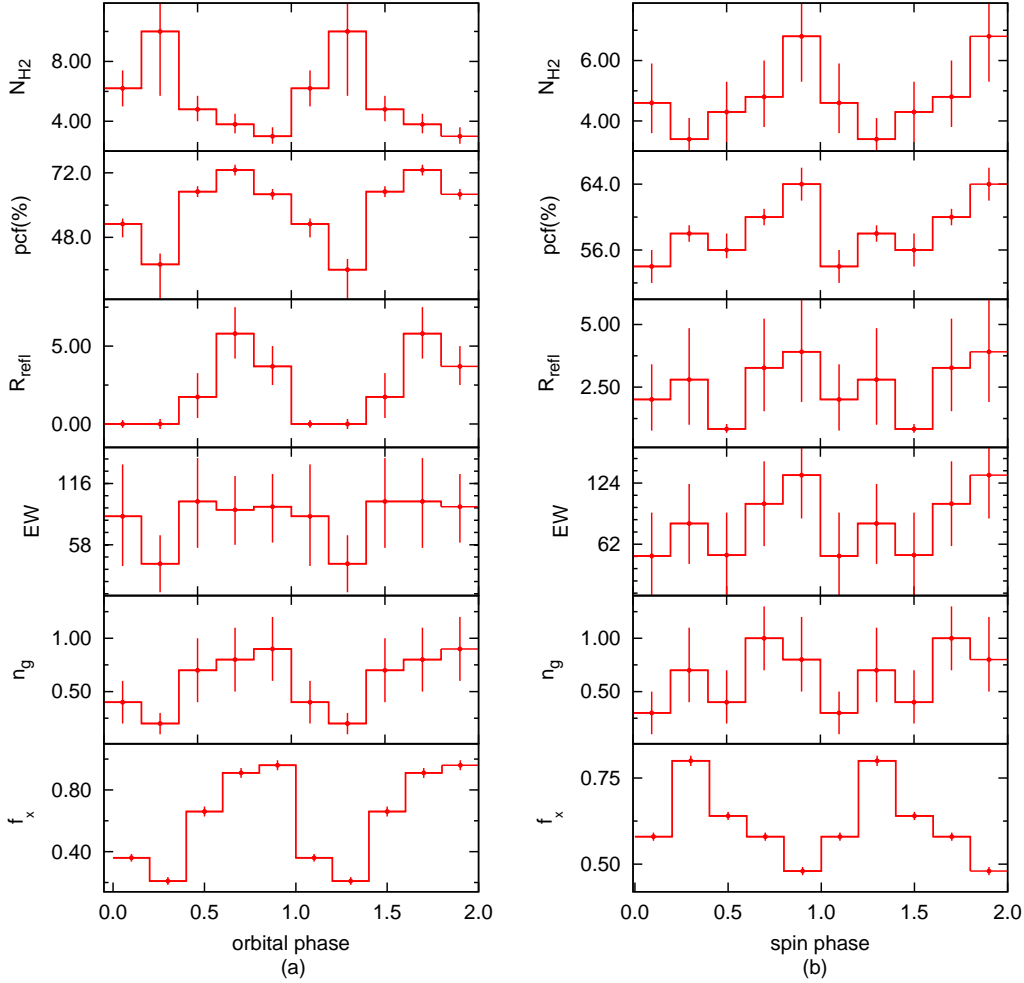


Figure 6. Variation of the best-fit spectral parameters as a function of orbital and spin phases. In both Figures (a) and (b), top to bottom panels show the variation of column densities (N_{H2}) due to partial covering of the X-ray source by neutral hydrogen, partial covering fraction (pcf), relative normalization of the reflection component (R_{refl}), equivalent width (EW) of fluorescence iron line, the normalization of Gaussian (n_g) component, and flux (f_x), where (N_{H2}) in units of 10^{22} cm^{-2} , EW in units of eV, n_g in units of 10^{-5} photons $\text{cm}^{-2} \text{ s}^{-1}$, and flux in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. Error bars are plotted with a 90% confidence limit for a single parameter.

2414. This indicates that accretion occurs in a stream-fed scenario where the WD has a relatively strong magnetic field (see Norton et al. 1999). Unlike the single-peaked X-ray modulations, such modulations were not detected in the optical domain of Paloma along with a long WD spin period. The amplitude of the optical modulations varies greatly from night to night, which is a common behavior for the IPs (see, for example, Welsh & Martell 1996). The disappearance of the double hump from one night of observation to another indicates that the beat period of Paloma is much shorter than the other near-synchronous polars.

We see that the amplitude of the rotational pulsation is independent of energy. This could be due to the occultation of X-ray emitting regions as WD rotates. However, there are many IPs where the amplitude of rotational pulsation increases with decreasing energy, which is consistent with photoelectric absorption in the accretion flow.

We have noticed the excess in the X-ray spectra of Paloma near 0.5 keV, which is well explained by low-temperature apec component. In order to account this excess, we have derived the unabsorbed soft (F_s) and hard (F_h) X-ray fluxes of $2.1^{+0.2}_{-0.1} \times 10^{-13}$ and $7.7^{+0.1}_{-0.1} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the energy band of 0.3 - 10.0 keV from the low- kT apec model and high- kT apec model, respectively. The softness ratio is then calculated by

using the formula $F_s/4F_h$ and the value is obtained as 0.0068, which closely matches with the softness ratio of IP V2400 Oph (Evans & Hellier 2007). The soft-X-ray excess is mostly prominent in the X-ray spectra of polars; however, the growing number of IPs (e.g., PQ Gem, NY Lup, GK Per, V405 Aur, and V2400 Oph) also shows the soft X-ray component. In many systems, this soft-X-ray excess was explained by the black-body component with a temperature less than 100 eV (e.g., Mason et al. 1992; Haberl et al. 1994; de Martino et al. 2004; Evans & Hellier 2007; Anzolin et al. 2008, 2009). However, in an IP IGR J17195–4100 the soft-X-ray excess was well fitted by a low-temperature apec component in X-ray spectra (Girish & Singh 2012). Kuipers & Pringle (1982) suggest that the soft-X-ray excess usually seen in polars due to blobby accretion, i.e., dense blobs of matter penetrate into the WD photosphere and the energy is thermalized to a black-body, but the main reason some IPs show soft-X-ray excess is simply that the heated region near the accretion footprints is not hidden by the accretion curtains while, in other IPs, the accretion footprint is hidden by the accretion curtains, the difference being the result of the system inclination and the magnetic colatitude (see Evans & Hellier 2007).

The variations in the absorption component (N_{H2}) are found to be minimum when the X-ray fluxes are maximum for both the spin and the orbital cycles. The self-absorption can

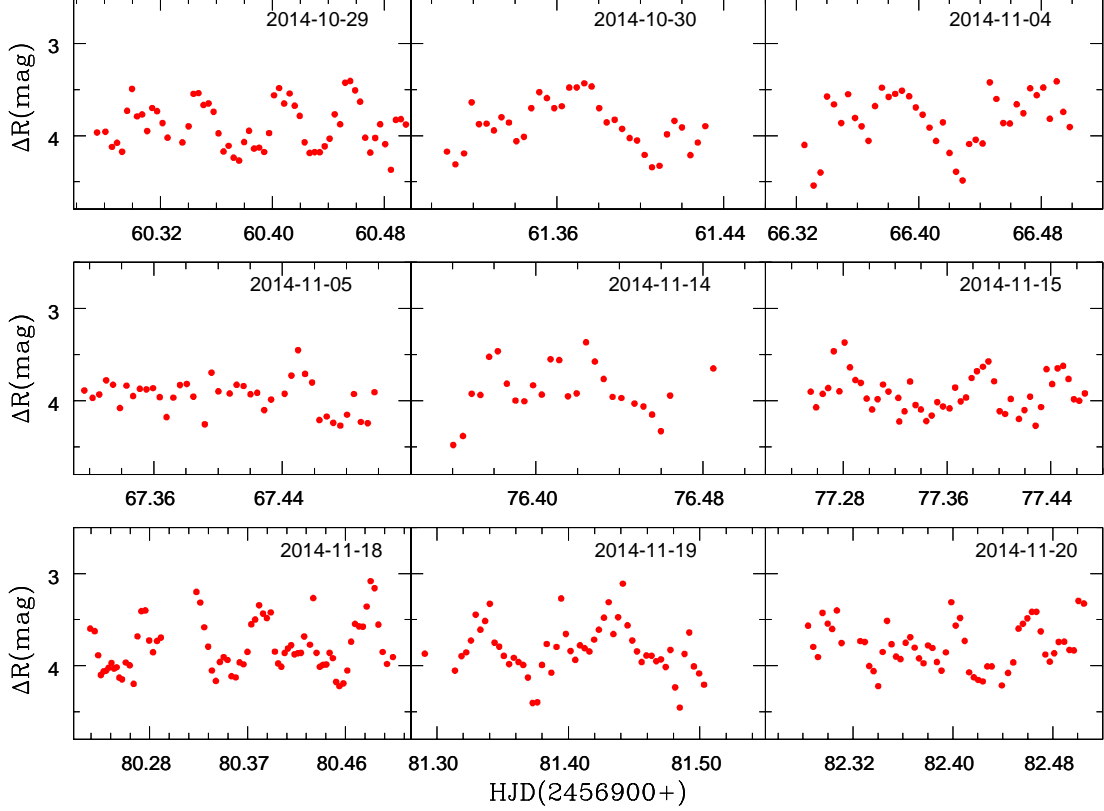


Figure 7. R-band light curve of Paloma. The observed dates are mentioned at the top of each panel.

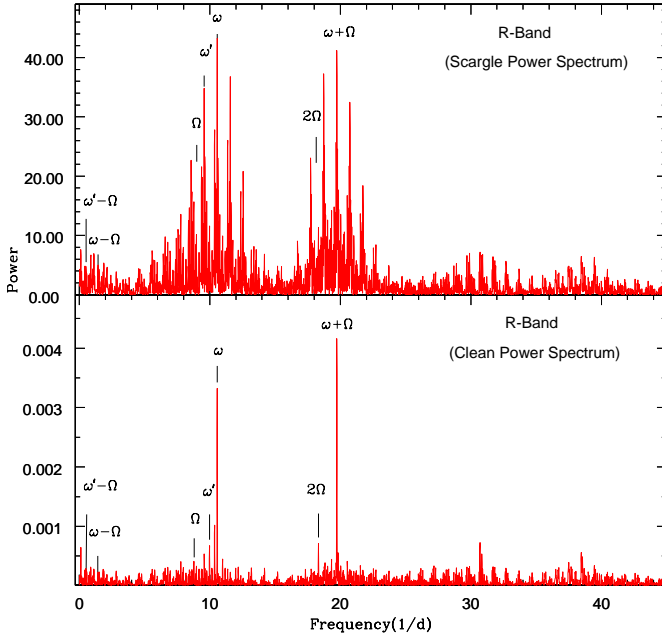


Figure 8. Power density spectrum of Paloma, computed from the combined photometric data. The top panel shows power spectra obtained using the Lomb–Scargle Periodogram, while the bottom panel shows the CLEANed power density spectrum.

cause such variation in an IP with the accretion curtain. The X-ray flux will be minimum due to the maximum absorption when the curtain is maximally in the line of sight, and the X-ray flux will be maximum when either the curtain moves away from the line of sight or when it thins down. The high value of the X-ray flux with the spin phase requires a small value of the covering fraction of the source by an absorber. This implies the least hindered view toward the accreting pole at this spin phase. The variations in the relative normalization of the reflection component are consistent with the EW of the iron emission line and their contribution is maximum at the rotational minimum phase. The correlated variations of pcf, EW, and R_{refl} with spin phase (in Figure 6) indicate that these variations support the accretion curtain scenario. The pcf, EW, and R_{refl} are found to be maximum at the minimum value of flux at spin phase. This could be due to the fact that the projected accretion area on the WD surface is larger and pointed toward the observer. The variations in the iron $K\alpha$ emission line flux closely resemble the variations in the X-ray flux in the 0.3–10.0 keV energy band, indicating that in the region where the line is produced there is no change in the accretion geometry, and are also visible at all times during the binary and rotation motion. The correlation of line flux with the average X-ray intensity may also indicate that the derived orbital and spin periods are true periods.

5. SUMMARY

To summarize, we find the following characteristics of Paloma, which are well explained by present optical and X-ray data.

1. Orbital and spin periods determined from the timing analysis of X-ray and optical data indicate that Paloma lies slightly away from the line of synchronization and it could be a transition object between polars and IPs.

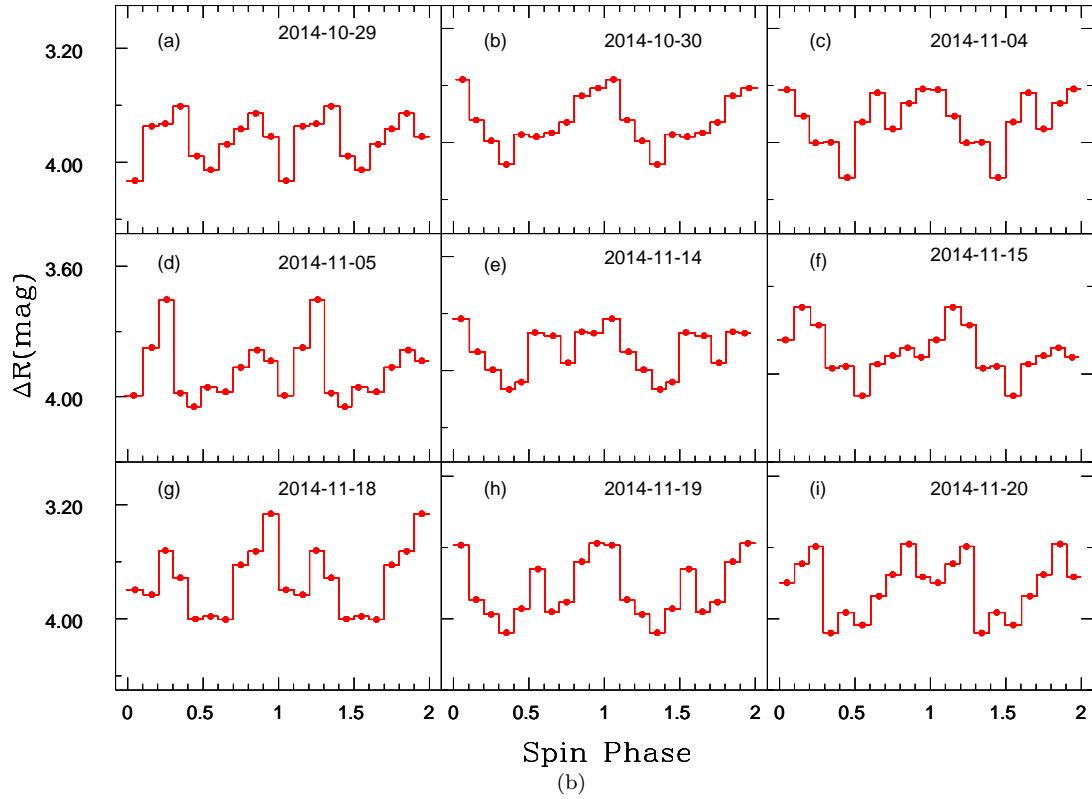
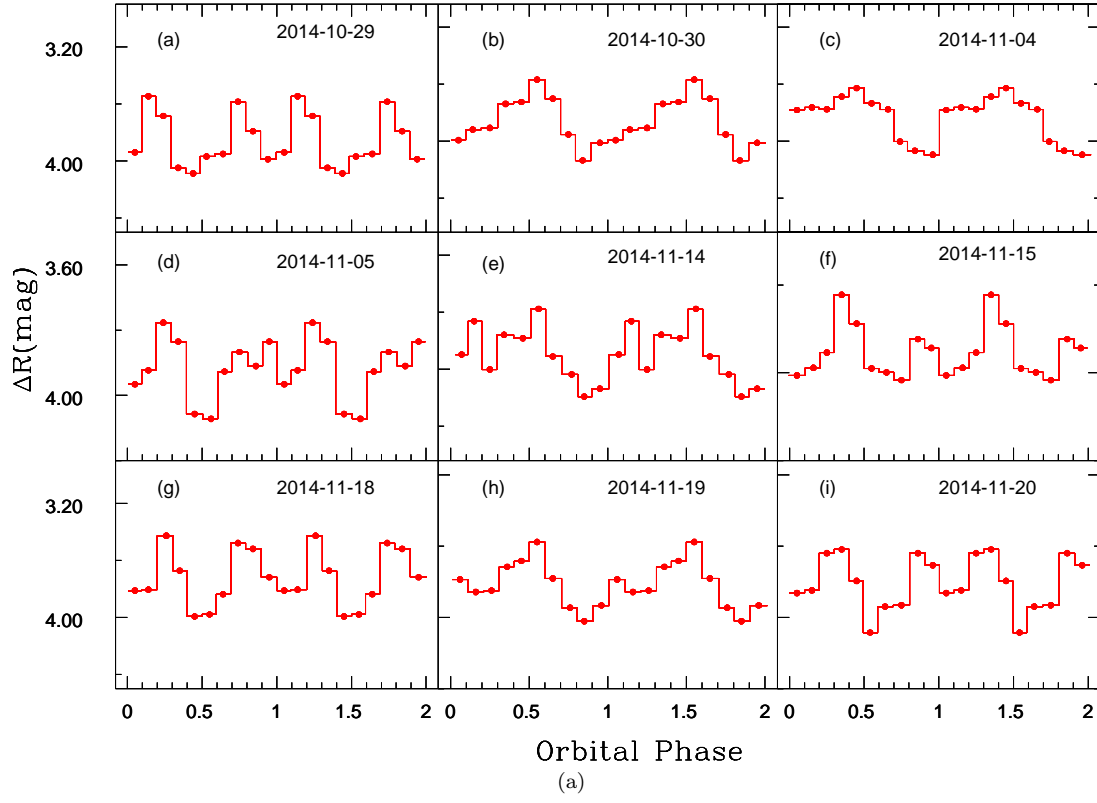


Figure 9. Orbital and spin-phase-folded light curves of Paloma in the R-Band on different dates of observations.

2. The X-ray power spectra obtained in different energy bands and the presence of significant peaks at spin, beat, and $2\omega - \Omega$ frequencies suggest that Paloma is a disk-less system.
3. The X-ray pulse is energy independent, which indicates that the spin pulsations could be originating due to the occultation of the emitting region by rotation of WD.
4. The soft-X-ray excess observed in the X-ray spectra of Paloma could be due to the accretion curtains, which are unable to hide the accretion footprints due to the highly inclined magnetic axis of the system.
5. A marginal detection of O VIII and O VII lines in the RGS spectra indicates the presence of the cooler optically thin emitting region.

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Facility: *XMM-Newton*

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